AFOSR-TR-97-0467

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		FINAL REPORT 01 May 93 - 30 Apr 97

4. TITLE AND SUBTITLE
Resonant Tunneling and Hot Electron Spectroscopy in Buried Rare-Earth Arsenide/Semiconductor Heterostructures

5. FUNDING NUMBERS
61102F
2305/ES

6. AUTHOR(S)
Dr. S. James Allen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California
Quantum Institute
Santa Barbara, CA 93106

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
United States Air Force
AFOSR/NE
110 Duncan Ave. Room B115
Bolling AFB DC 20332-8080

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-93-1-0329

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A new materials arena has been opened for quantum electron transport devices based on magnetic, semi-metal compound semiconductor heterostructures. Epitaxial ultrathin films of a rare earth arsenide, ErAs, were grown in GaAs semiconductors. The dissimilarities between the ErAs, a magnetic semimetal, and the compound semiconductor make possible the fabrication of three terminal resonant tunneling transistors with ultra thin semi-metal quantum wells. Resonant tunneling through semi-metal quantum wells was observed for the first time. A strong coupling of the magnetization and the resonant tunneling was discovered that demonstrates magnetization controlled resonant tunneling. Nano-composites of ErAs / GaAs were also grown. Electron transport in these systems exhibits giant magneto-resistance, magnetization controlled island to island electron hopping transport. This research program has opened the possibility of high density, non-volatile information storage and processing based on magnetic, semi-metallic, quantum structures grown and integrated into compound semiconductor heterostructures.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	6
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

Final Report

F49620-93-329 "Resonant tunneling and hot electron spectroscopy in buried rare-earth arsenide/semiconductor heterostructures" and

AASERT F49620-93-0440 "Non-linear terahertz electronics with self organized rare-earth arsenide semi-metal/semiconductor composites".

The rare-earth arsenides are magnetic, semimetallic compounds that can be grown epitaxially on III-V compound semiconductors like GaAlAs. These systems open the potential for novel electronics and photonics based on magnetic, semimetal semiconductor heterostructures. The objective of this work was to explore the magnetics, transport and optics and assess the importance of this material system in future magnetics, electronics and photonics.

The technical approach followed several avenues.

1. Three terminal resonant tunneling diodes comprised of ErAs quantum wells in AlGaAs heterostructures were successfully grown, fabricated and tested.

2. Nano-composites of ErAs islands were successfully grown and used to explore magnetization controlled island - island hopping transport.

3. ErAs islands were imbedded in highly doped 2-dimensional electron gases to control electron percolation and produce random, self organized quasi-optical Schottky diode arrays for terahertz harmonic generation.

4. Near IR photo response of ErAs / GaAs nano-composites was measured to assess the potential for fast fast photo-conductive detectors.

The following milestones and breakthroughs were achieved.

- The contrasting electrical, chemical and structural properties of the ErAs and III-V semiconductors allows ion implant isolation of buried ErAs semimetal from the doped host semiconductor. Followed by contact anneal, selective and specific ohmic contact can be made to ultra thin buried semi-metal layers in semiconductor heterostructures. A simple and effective method fabricating three terminal resonant tunneling diodes follows.

- Resonant tunneling through semimetal quantum wells was observed for the first time.

- Using the unique properties of these three terminal resonant tunneling diodes, it was discovered that electrons tunnel through resonant hole channels in the ErAs quantum well resonant tunneling diodes.

- The dispersion relation of the resonant hole channels was measured.

• A giant spin splitting of the resonant channel was discovered and is understood to be caused by the exchange interaction between the Er 4f spins and the resonant hole channel.

• Following measurements of the hole dispersion we are able to measure the dispersion of the exchange coupling of the Er 4f spins and the resonant holes.

• ErAs islands can be grown with sizes controlled by the growth temperature of the substrate. Superlattices of 2-dimensional sheets ErAs islands can be grown.

• A giant negative magneto-resistance was discovered that points to magnetization controlled hopping conduction between islands.

• Terahertz harmonic generation from self organized Schottky diode arrays has been measured. The predicted enhancement is not observed.

• Preliminary measurements on the near IR photo response indicate that the internal photoemission in ErAs / GaAs nano-composites may over another route to fast near IR photo detectors

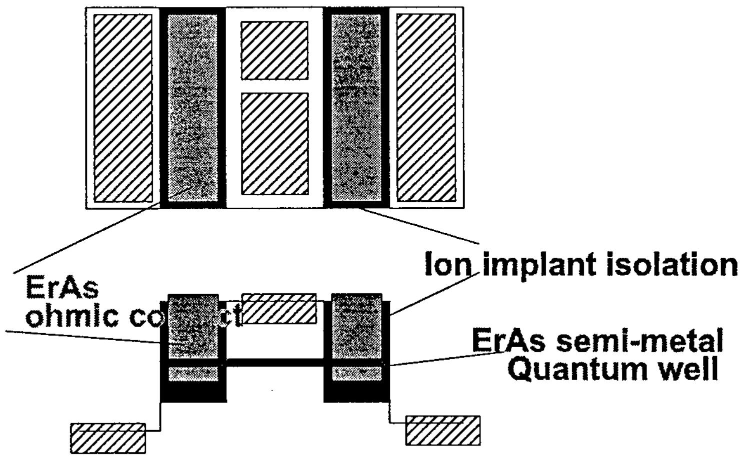

Fig. 1 Ion implantation can render doped regions of the heterostructure insulating without altering the conductivity of ultra-thin buried metal layers.

Three terminal resonant tunneling diodes. Ion implantation has little effect on the electrical properties of ultra thin semi-metals. As a result regions of the surrounding III-V semiconductor can be rendered insulating leaving a thin (>0.8nm) protruding metallic sheet. (Fig. 1.) (It was discovered in earlier work that because of the peculiarities of the band structure of ErAs there was no semi-metal to semiconductor transition at thicknesses down to 3 monolayers.) Ohmic contact to this sheet leaves a three terminal device in which the control electrode can be as thin as 0.8nm. An abiding materials problem, however, is the

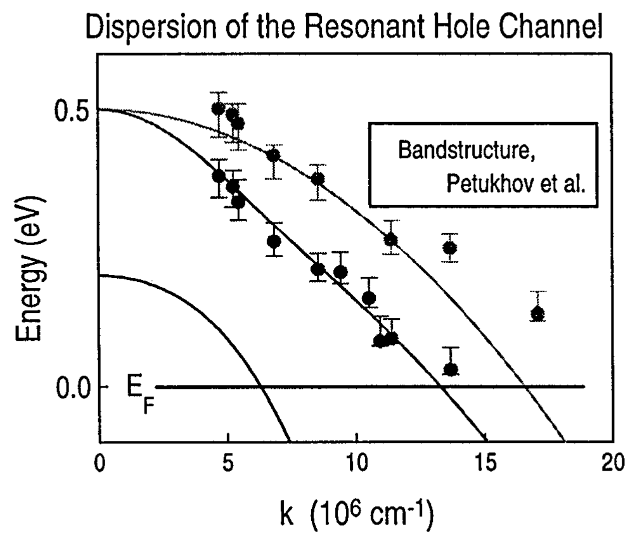

Fig. 2 The dispersion of the hole channels determined from the thickness dependence of the quantum well potential for resonant tunneling.

quality of the III-V semiconductor grown on top of the rare earth arsenide (ReAs). As a result, while the semi-metal quantum well can be contacted and used to determine the potential in the quantum well, it is difficult to isolate it from the top III-V epilayers. None the less, the semimetal quantum well enables one to define and measure the Fermi energy. This is not possible in conventional III-V heterostructures.

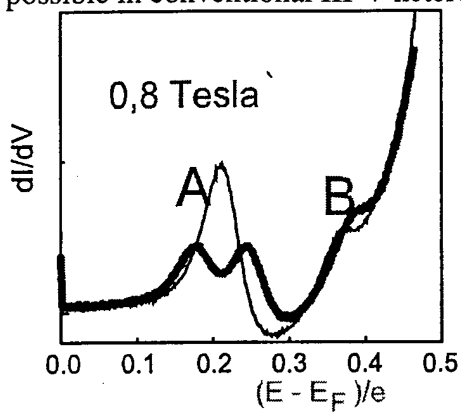

Fig. 3 The resonant channels are distinguished by their dependence on magnetic field.

Two resonant channels were identified and distinguished by there behavior in a magnetic field. Remarkably, a systematic study of the dependence on the quantum well thickness revealed that the resonant channels were hole channels and their dispersion was measured. (Fig. 2)

In modest magnetic fields, a large splitting of the channels was observed which depended on the orientation of the magnetic field. (Fig. 3.) The splitting was measured to be of the order of .1 eV or ~ 1000K. It is caused by the exchange interaction between the 4f spin and the resonant hole states.

By measuring the splitting as a function of the thickness, the dispersion or wave vector dependence of the exchange coupling could be determined. It appears to vanish as k approaches 0. This is expected since the states at $k=0$ are predominately on the As and the contact exchange interaction with the 4f spin should be suppressed.

This research points to the possibility of fabricating a device in which the resonant tunneling is controlled by the orientation of the magnetization of a ferromagnetic film.

Growth of ErAs / GaAs nanocomposites. Below 3 monolayers of ErAs the material forms islands. The island size has been found to be determined by the substrate temperature. Around 600 C the islands are of the order of 2 nm , whereas at growth temperatures approaching 700 C the islands are nearing 100 nm. (Fig. 4)

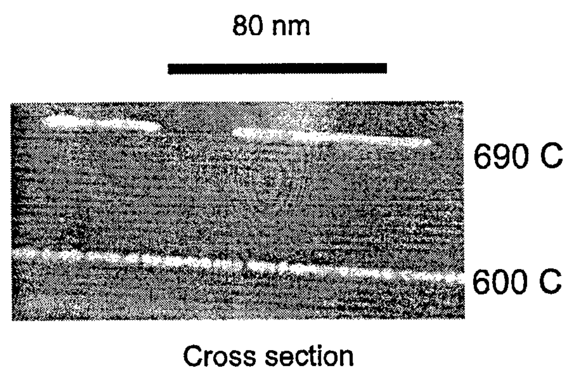

Fig. 4 ErAs island depends on substrate temperature.

Giant magneto resistance and magnetization controlled island hopping .Resistivity measurements at low temperature in a magnetic field reveal a striking negative magneto-resistance. For some nano-composites the resistance drops some 4 orders of magnitude in a 2 Tesla field. (Fig. 5) Theoretical models developed by Petukhov et al. point to size dependent magnetization fluctuation characteristic of nanometer scale paramagnetic particles. The relative orientation determines the hopping rate. More needs to be done establish the mechanism and its dependence on material parameters.

Nano-composites of ErAs / GaAs with doping layers appear like random Schottky diode arrays. Enhanced non-linearity's are expected from two different perspectives. At percolation

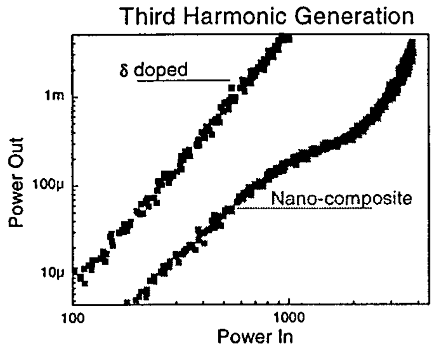

Fig. 6 Terahertz third harmonic generation (600 GHz in 1.8 THz out) from a doped layer and a doped layer with ErAs semi-metal islands.

non-linearity's should be amplified by the strong electric fields that appear at the constrictions. From another perspective we have an array of back to back Schottky diodes that should be intrinsically non-linear.

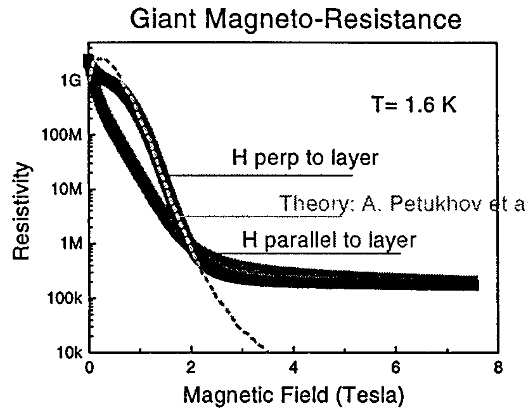

Fig. 5 A giant negative magneto-resistance signals magnetization controlled hopping transport between the islands.

Early results are not encouraging. The insertion of the semi-metal islands in an otherwise uniform 2 dimensional electron gas results in lower non-linear response. (Fig. 6).

Near IR Photoresponse. Internal photoemission from small ErAs metal particles could lead to fast sensitive near IR photo detectors. They have the same features as does LT GaAs with the As semi-metal cluster replaced by the ErAs. The spectrum of the photo response shows threshold consistent with internal photo-emission from the ErAs particles and that is consistent with the accepted Schottky barrier heights between ErAs and GaAs. Preliminary measurements on the time response find it fast enough to warrant further investigation.

Publications.

Sadwick, L.P., Lee, P.P., Patel, M., Nikols, M., et al. "Epitaxial dysprosium phosphide grown by gas-source and solid-source MBE on gallium arsenide substrates.", J. of Crystal Growth, July 1996, vol.164, (no.1-4):285-90.

Bogaerts, R., Herlach, F., De Keyser, A., Peeters, F.M., et al., "Experimental determination of the Fermi surface of thin $Sc_{1-x}Er_xAs$ epitaxial layers in pulsed magnetic fields.", Phys. Rev. B (Condensed Matter), 15 June 1996, vol.53, (no.23):15951-63.

Brehmer, D.E., Kai Zhang, Schwarz, Ch.J., Chau, S.-P., et al., "Resonant tunneling through rare earth arsenide, semimetal quantum wells.", Solid-State Electronics, June 1996, vol.40, (no.1-8):241-4.

Brehmer, D.E., Kai Zhang, Schwarz, C.J., Chau, S.-P., et al., "Resonant tunneling through ErAs semimetal quantum wells.", Applied Physics Letters, 28 Aug. 1995, vol.67, (no.9):1268-70.

Zhang, K., Brehmer, D.E., Allen, S.J., Jr., Palmstrom, C.J. "Resonant tunneling in semi-metal/semiconductor, ErAs/(Al,Ga)As, heterostructures." Proceedings of the Twenty-First

International Symposium. Edited by: Goronkin, H., Mishra, U. Bristol, UK: IOP Publishing, 1995. p. 845-50.

Brehmer, D.E., Ibbetson, J.P., Kai Zhang, Petukhov, A.G., et al., "Resonant tunneling through (Al,Ga)As/ErAs/(Al,Ga)As, semi-metal quantum wells." Semiconductor Heteroepitaxy. Growth, Characterization and Device Applications, Edited by: Gil, B., Aulombard, R.-L. Singapore: World Scientific,1995. p. 672-5.

Bogaerts, R., De Keyser, A., Herlach, F., Peeters, F.M., et al., "Quantum oscillations in the Hall effect of thin $Sc_{1-x}Er_xAs$ epitaxial layers buried in GaAs." International Conference, High Magnetic Fields in the Physics of Semiconductors. Edited by: Heiman, D. Singapore: World Scientific, 1995. p. 706-9.

Bogaerts, R., De Keyser, A., Herlach, F., Peeters, F.M., et al., "Size effects in the transport properties of thin $Sc_{1-x}Er_xAs$ epitaxial layers buried in GaAs." Solid-State Electronics, April-June 1994, vol.37, (no.4-6):789-92.

Allen, S.J., Brehmer, D., Palmstrom, C.J. "Novel electronics enabled by rare earth arsenides buried in III-V semiconductors.", Rare Earth Doped Semiconductors Symposium , Edited by: Pomrenke, G.S., Klein, P.B., Langer, D.W. Pittsburgh, PA, USA: Mater. Res. Soc, 1993. p. 307-17.

Schmidt, D.R., Ibbetson, J.P., Brehmer, D.E., Palmstrom, C.J. and Allen, S.J., "Giant magnetoresistance of self assembled ErAs islands in GaAs.", to be published Mater. Res. Soc.

Presentations:

Brehmer, D.E., "Resonant tunneling through rare earth arsenide, semimetal quantum wells.", Seventh International Conference on Modulated Semiconductor Structures, Madrid, Spain, 10-14 July 1995.

Brehmer, D.E., "Resonant tunneling in semi-metal/semiconductor, ErAs/(Al,Ga)As, heterostructures.", Twenty-First International Symposium on Compound Semiconductors, San Diego, CA, USA,18-22 Sept. 1994.

Brehmer, D.E., "Resonant tunneling through (Al,Ga)As/ErAs/(Al,Ga)As, semi-metal quantum wells." Semiconductor Heteroepitaxy. Growth, Characterization and Device Applications, Montpellier, France, 4-7 July 1995.

Bogaerts, R. "Quantum oscillations in the Hall effect of thin $Sc_{1-x}Er_xAs$ epitaxial layers buried in GaAs.", 11th International Conference on High Magnetic Fields in Semiconductor Physics, Cambridge, MA, USA, 8-12 Aug. 1994.

Bogaerts, R., "Size effects in the transport properties of thin $Sc_{1-x}Er_xAs$ epitaxial layers buried in GaAs., Sixth International Conference on Modulated Semiconductor Structures, Garmisch-Partenkirchen, Germany, 23-27 Aug. 1993.

Allen, S.J., "Novel electronics enabled by rare earth arsenides buried in III-V semiconductors." Rare Earth Doped Semiconductors Symposium, San Francisco, CA, USA, 13-15 April 1993.

Zhang, K., "Resonant tunneling in semi-metal/semiconductor, ErAs/(Al,Ga)As, heterostructures.", Rare Earth Doped Optoelectronic Materials Workshop, 16-17 June 1994, Hughes Research Lab, Malibu CA.

Personnel participation in this contract:

Name	Position	Current Status
K. Zhang	Post-doctoral researcher	EG&G
S.-P. Chau	Undergraduate researcher	EG&G
D.E. Brehmer	Graduate student researcher	Writing dissertation
D. Schmidt	Graduate student researcher	Research in progress
S. Rausch	Diploma student, Karlsruhe (without salary support)	Writing Diploma-arbeit
James Ibbetson	Post-doctoral researcher (without salary support)	Continuing
Frank Hegmann	Post-doctoral researcher	University of Alberta
C. Palmstrom	Consultant	Faculty, U. Minnesota